Correction of spherical aberration for an electrostatic gridded lens

Alexander Pikin and Ahovi Kponou
Brookhaven National Laboratory, Upton, New York 11973, USA

(Received 10 June 2008; accepted 1 September 2008; published online 10 December 2008)

Two methods to correct spherical aberration in electrostatic gridded lenses have been studied using ray-tracing simulations. Both methods are based on modifying the electrostatic field on the radial periphery of the lens. In the simplest case, the modification is done by extending the grid support axially. In the second method, the electric field on a radial periphery of the lens is modified by applying optimum voltage on an isolated correcting electrode. It is demonstrated that, for a given focal length, the voltage on this lens can be optimized for minimum aberration, and also that these lenses reduce the emittance growth of the ion beam. © *2008 American Institute of Physics.*
[DOI: 10.1063/1.3030857]

I. INTRODUCTION

The gridded lens is a frequent lens of choice for transporting space charge-dominated ion beams where beams fill up a significant fraction of a beam line cross section, and minimum spherical aberration is required. There are few alternatives to the gridded lens for use where beam focusing or defocusing is needed. Like other electrostatic lenses, the gridded lens has spherical aberration which is caused primarily by different focusing properties of the electric field at different radii. Since the main contributor to the emittance growth in a beam line is spherical aberration produced by the optical elements (primarily lenses), it is important to reduce this effect, especially when the ion beam fills a significant fraction of the lens aperture.

The idea of correcting the lens aberration by forming the foils/meshes with a simple spherical shape has been discussed,[1,2] and with more complex shapes which follow the shape of equipotentials needed for aberration-free focusing.[3] However, there is a limit to aberration reduction for a gridded lens. This limit is due to the discrete structure of the mesh, which results in microfocusing of the beam by individual cells. This effect is studied in Refs. 4 and 5. The goal of this work is to use ray-tracing simulations to study two methods of reducing spherical aberration in a single-grid lens, for beams with large filling factors of the lens.

II. METHODS OF ABERRATION CORRECTION

We consider a simple one-grid lens with two cylindrical mounting rings on both sides of the grid (Fig. 1). This lens is mounted inside an axially symmetric grounded pipe of larger inner diameter (i.d.). The i.d. of the cylindrical rings determines the lens aperture.

A. Gridded lens with rings at the same potential as the grid (unipotential lens)

Typically, the focusing property of the electrostatic lens on its radial periphery is higher than near the axis and, for this reason, the edge of the ion beam is focused stronger than its central part, thus producing spherical aberration. Reducing the focusing strength on the periphery of the lens would reduce spherical aberration.

The symmetrical rings on both sides of the grid are the mounting for the grid and they can be used to shape the electrostatic field at the periphery of the lens. In the simple case when the rings have the same potential as the grid, the radial component of the electric field on the periphery of the lens can be reduced by extending these rings axially. The main dimensions in the model presented in Fig. 1 are for a lens which was built in a two-sided vacuum flange for use in a 6 in. vacuum pipe.

The optical simulations were done with program TRAK.[5] 500 trajectories parallel to the axis with a fixed energy of $E_{\text{ion}}=17.5$ keV/charge, randomly distributed with uniform average density over a circular cross section, and with zero current (beam space charge ignored), were used. Since the initial emittance of the beam is zero, the final emittance (rms normalized) can be interpreted as emittance growth caused by the lens, or as an acquired emittance. The focal distance here is defined as the distance, averaged over all tracks, from the grid to the intersections of the tracks with the longitudinal axis. For a fixed gap of 2.5 mm between grid and rings,

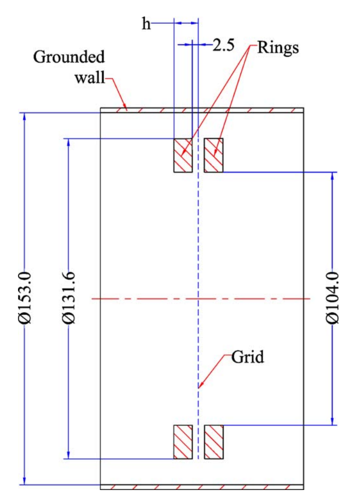

FIG. 1. (Color online) Schematic of the gridded lens in a pipe used for ray-tracing simulations.

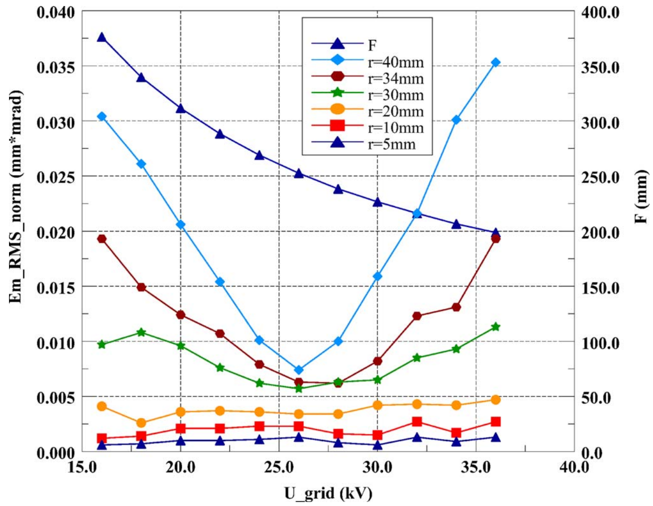

FIG. 2. (Color online) Dependences of focal length F (triangles) and acquired emittance Em_RMS_norm on the grid voltage U_grid for different ion beam radii. The length of the ring is $h=30$ mm.

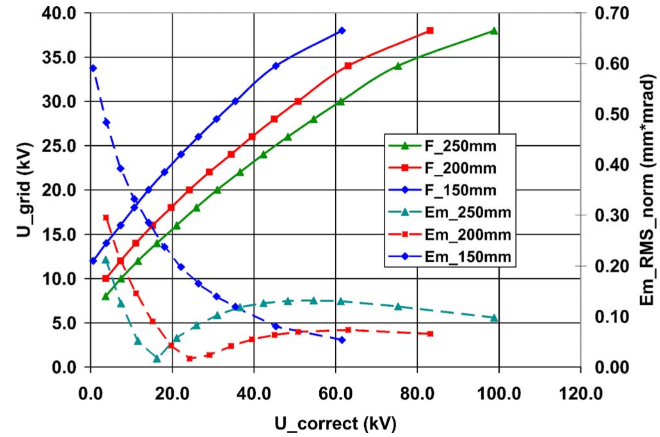

FIG. 4. (Color online) Dependences of the voltages on the grid U_grid (solid lines) required for focal lengths $F=250$ mm, $F=200$ mm, $F=150$ mm and the acquired rms normalized emittance of the ion beam E_RMS_norm (broken lines) on a correcting electrode voltage U_correct. The ion beam radius is 40 mm.

we studied the effect of the ring length on the focusing strength of the lens, and on the emittance growth. For a ring length $h=30$ mm, the results of simulations for different ion beam radii are presented in Fig. 2.

With beam radius larger than 20 mm the dependence of emittance growth on the grid voltage has a minimum, which is more pronounced with larger beam radius. The results the simulations for a unipotential lens with varying h (see Fig. 1) are presented in Fig. 3.

With increased length of the ring, the radial electric field component in the vicinity of the ring decreases, and this helps to reduce aberration. The radial electric field component at smaller radii is also affected, although to a smaller extent than near the ring. The net result of the increased ring length is reducing the aberration as well as the focusing strength of the lens. One can see that with increased length of the ring, it takes a greater lens voltage to get the same focal distance. The dependence of emittance growth for a given focal length on h, the length of the ring, shows a minimum for each focal length. Minimum emittance growth occurs at higher h as the focal length increases.

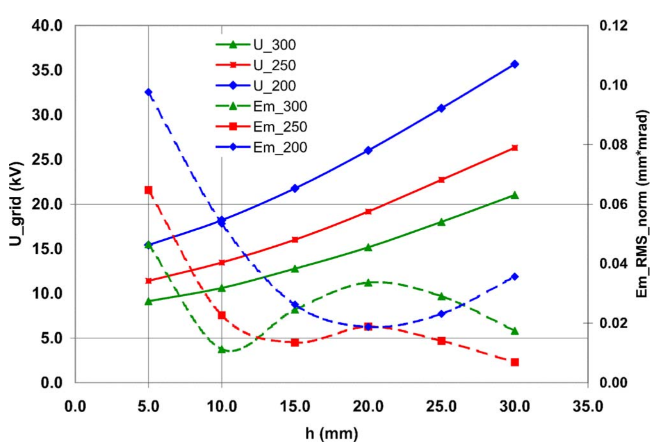

FIG. 3. (Color online) Dependences of voltages on the grid U_grid (solid lines) required for different focal lengths ($F=300$ mm, $F=250$ mm, and $F=200$ mm) and the acquired rms normalized emittance of the ion beam Em_RMS_norm (broken lines) on the length of rings h. The ion beam radius is 40 mm.

B. Gridded lens with isolated correcting electrode

Since for beams with large radii the unipotential lens has a relatively short range of focal length where the emittance growth is small, it seems attractive to make a lens whose spherical aberration correction can match the focal length. The solution is to modify the electrostatic field at the edge of the lens by applying a suitable potential to the rings on both sides of the grid; the rings must be electrically isolated from both the grid and ground. With the same potential on these rings they can be viewed as a correcting electrode which modifies the electrostatic field by changing voltage, just as the unipotential lens discussed above does by changing length.

The geometry of the model is similar to that shown in Fig. 1. Both rings have the same potential and they are isolated from both the grid and the ground. The rings have a fixed length of $h=10$ mm, and a fixed gap between grid and rings of 2.5 mm. For each voltage on the correcting electrode, the voltages on the grid were found which focused the ion beam to 150, 200, and 250 mm from the grid. The results are presented in Fig. 4.

The similarity of Figs. 3 and 4 suggests that the effect of increased correcting electrode voltage here is similar to the effect of increased length of the rings in the unipotential case. For a fixed voltage on the grid, increasing the voltage on the correcting electrode makes the focusing of the lens weaker near the fringes than near the axis, which results in lower spherical aberration. At the same time the focusing power of the lens is also reduced.

The effect of the correcting electrode voltage on the ion trajectories is demonstrated in Fig. 5. Insufficient voltage on the correcting electrode compared to what is needed for optimal focusing results in overfocusing of the peripheral trajectories compared to near-axis trajectories [Fig. 5(a)]. With increased voltage on the correcting electrode the radial component of electrostatic field on the radial periphery decreases.

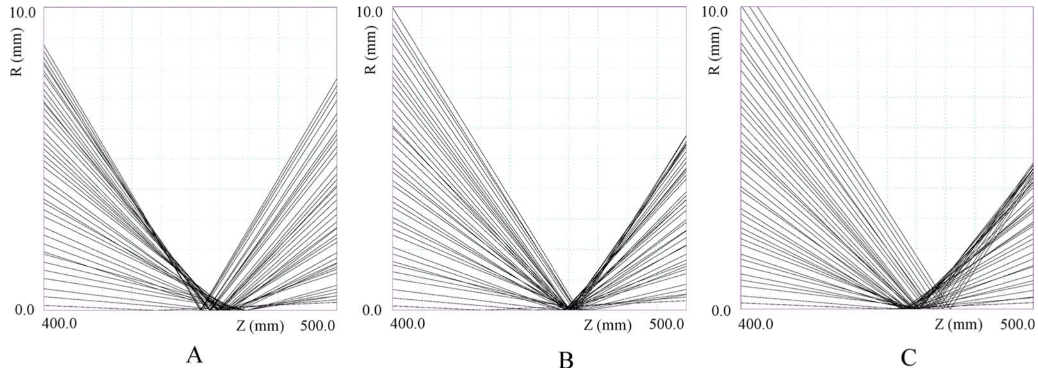

FIG. 5. (Color online) Trajectory plots at focal distance $F=250$ mm for overfocusing conditions of peripheral trajectories [(a) $U_{grid}=12$ kV, $U_{contr}=11.59$ kV, $\varepsilon_{RMS\_norm}=0.0519$ mm mrad], for optimal focusing [(b) $U_{grid}=14$ kV, $U_{contr}=16.21$ kV, $\varepsilon_{RMS\_norm}=0.0171$ mm mrad) and for underfocusing conditions [(c) $U_{grid}=16$ kV, $U_{contr}=21.06$ kV, $\varepsilon_{RMS\_norm}=0.0574$ mm mrad]. The grid is at $z=209$ mm.

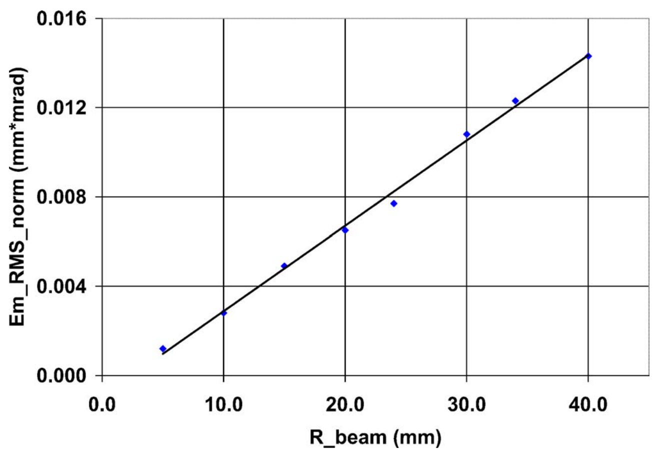

FIG. 6. (Color online) Dependence of the emittance growth of ion beam in a gridded lens Em_RMS_norm on the radius of ion beam R_beam for voltages optimized for focal distance $F=202$ mm. The solid line is a linear fit.

As a result the trajectories crossing over becomes smaller [Fig. 5(b)], and with further increase in this voltage we have insufficient focusing of the peripheral trajectories [Fig. 5(c)], which increases the emittance.

The dependence of emittance growth on beam radius when the lens is optimized for focal distance $F_{focal}=202$ mm is presented in Fig. 6. Within beam radii studied the acquired emittance is approximately proportional to the beam radius.

The curves in Fig. 7 allow one to find an optimum combination of voltages on the grid and on the correcting electrode for a desired focal distance with minimum spherical aberration for a given lens geometry and beam energy. The performances of different types of electrostatic lenses having an i.d. of 104 mm are presented in Fig. 8 for identical parameters of ion beam.

This graph demonstrates that a unipotential gridded lens has advantage over the lens with isolated correcting electrodes in a certain range of focal length it is optimized for. A unipotential lens with $h=30$ mm has some lower aberration than the lens with isolated correcting electrode in an optimum range of focal distance. The lens with isolated elec-

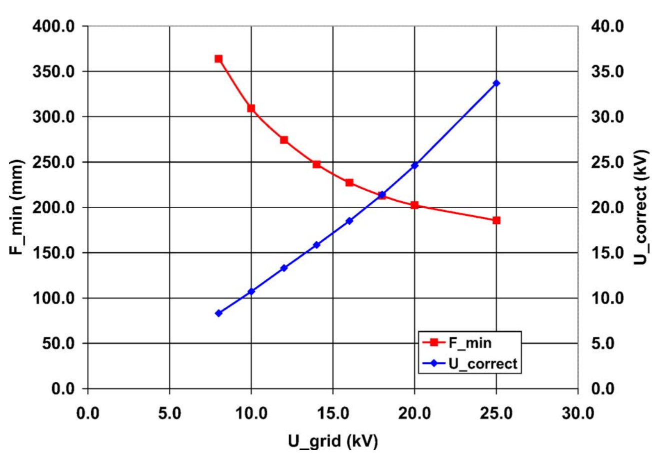

FIG. 7. (Color online) Dependences of voltage on the correcting electrode $U_{correct}$ and corresponding focal distance F_{min} of the lens on the grid voltage U_grid for focusing with minimum aberration. Beam radius $r_{beam}=40$ mm.

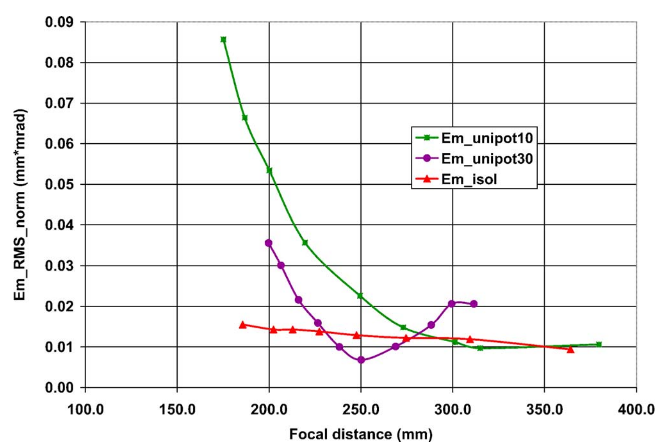

FIG. 8. (Color online) Dependence of the beam emittance growth Em_RMS_norm in the lens with the same aperture of 104 mm on the focal distance for unipotential gridded lenses with $h=10$ mm and $h=30$ mm, and for gridded lens with isolated correcting electrodes ($h=10$ mm) optimized for minimum aberration.

trodes retains low aberration over a wide range of focal distances.

III. SUMMARY

A method of correcting spherical aberration by single-grid lens by increasing the length of the rings on the radial periphery of the grid is effective for lens application with fixed focal distance. For applications requiring variable focusing strength a gridded lens with isolated electrodes has an advantage. It allows for low emittance growth over a much wider range of the focal length.

ACKNOWLEDGMENTS

This work was performed under the auspices of the U.S. Department of Energy. The authors want to thank James Alessi and Masahiro Okamura for fruitful discussions.

[1] J. W. Johnson, IEEE Trans. Nucl. Sci. **12**, 765 (1965).
[2] M. Kato, J. Vac. Sci. Technol. A **13**, 2255 (1995).
[3] W. D. Meisburger and E. H. Jacobsen, Optik (Jena) **62**, 359 (1982).
[4] D. L. Williams, F. H. Read, and N. J. Dowring, Nucl. Instrum. Methods Phys. Res. A **363**, 120 (1995).
[5] See: http://www.fieldp.com/.